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ON POSITIVE AND NEGATIVE IONOSPHERIC STORMS

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A study is made of the intense storms of March 13–15, 1989 (D_{st} = –600nT), October 20–21, 1989 (D_{st} = –266 nT) and April 1–2, 1973 (D_{st} = –211 nT) in regards to the appearance of positive storm before the beginning of a geomagnetic disturbance in the mid-latitudes and the occurrence of strong negative phase at the equator. F2 region global structure response to the geomagnetic storms was studied using f_{o}F2 data obtained during the storms from a global network of ionosonde stations. Investigated phenomena were only observed, on October 20, 1989, in only three of the nineteen plots representing ∼16% occurrence for the case study of March and October 1989 storms: the positive storms at Slough (54.4°N) and Uppsala (59.86°N) and a negative storm at Ouagadougou (12.4°N). These ionospheric storms were caused by the southward turning of B_z at ∼2100 UT on October 18 which got to a change in B_z of $\delta B_z = 12.2$ nT at 2300 UT on October 18. In the case of the storm of April 1–2, 1973, the phenomena had ∼69% occurrence: the positive storms at Wakkanai (45.4°N), Akita (39.7°N), Kokubunji (35.7°N), Kiev (50.5°N) Sofia(42.7°N), Ottawa (45.4°N), Boulder (40.0°N) and Point Arguello (35.6°N) and a negative storm at Manila (14.7°N). These ionospheric storms appear to be caused by the southward turning of B_z at ∼1500 UT which got to a change in B_z of $\delta B_z = 13.6$ nT at 1900 UT on March 31. The non explanation of these phenomena before now is because in the studies of ionospheric storms it is assumed that the beginning of any particular disturbance is defined by the onset of the magnetic storm. The use of sudden storm commencement (SSC) and main phase onset (MPO) for fixing the beginning of magnetic and ionospheric storms is fraught with problems that render a determination of the exact onset time difficult. The notion of onset of the magnetic storm as a prevailing idea restricted the geoeffectiveness of the solar wind to post onset time thereby foreclosing the explanation of any aspect of the morphology of ionospheric storms whose origin precede the onset reference time.

Keywords: D(f_{o}F2) maximum; geomagnetic storm; ionospheric F2 region; main phase onset (MPO); morphology; sudden storm commencement (SSC)

1. Introduction

The F2 region response to a geomagnetic storm that is known as ionospheric storm consists of positive and negative phases. According to Danilov (2001), the principal features of the positive and negative phase distribution and variations have been explained on the basis of the principal concept: during a geomagnetic disturbance there is an input of energy into the polar atmosphere, which changes thermospheric parameters, such as composition, temperature and circulation. Composition changes directly influences the electron concentration in the F2 region. The circulation spreads the heated gas to lower latitudes. The conflict between the storm-induced circulation and the regular one determines the spatial distribution of the negative and positive phases in various seasons. However, there are still some unsolved problems; two of the acute ones, according to Danilov (2001), are the appearance of positive storm before the beginning of a geomagnetic disturbance in the mid-latitudes and the occurrence of strong negative phase at the equator. To study these phenomena we have analysed interplanetary and geomagnetic data as well as data from global network of ionosonde stations obtained during the intense geomagnetic storms of the maximum phase of solar cycle 22 and the intense geomagnetic storm of April 1–2, 1973. During the April 1–2, 1973 geomagnetic storm, the resulting ionospheric storm was worldwide and extended to very low latitudes. This paper presents an attempt to investigate these intense magnetic storms in regards to the appearance of positive storm before the beginning of a geomagnetic disturbance in the mid-latitudes and the occurrence of strong negative phase at the equator.

The maximum phase of solar cycle 22 brought about two remarkable periods of intense geomagnetic and ionospheric disturbances whose investigation is of considerable interest for the understanding of the morphology of ionospheric storms and solving of practical problems. First was the March 1989 period which started on March 6th with the appearance of a large sunspot region on the eastern edge of the sun and a remarkable solar flare of X-ray class of X15.0. The next 14 days produced 11 “X class” flares and 48 “M class”. However, the most outstanding feature of the interval occurred on March 13–14 with one of the largest geomagnetic storms in the last 50 years. The March 13–14 storm had profound effects on earth and in space. Power systems in Canada and Sweden failed as large electric currents were induced in power lines and tripped protective relays. Increased atmospheric drag, resulting from the expansion of the earth’s outer atmosphere during the disturbance, altered the orbits of many satellites with the result that NASA lost track of some of them for a short period. Satellite navigation systems failed to operate and High Frequency (HF) communication systems were also out of action. Aurorae were sighted at quite equatorial latitudes. October 1989 was other interesting interval and consists in part a large proton event resulting in a remarkable solar flare which occurred on October 19 with the X-ray class of X13.0 near the central meridian of the Sun. The severe geomagnetic storm of October 20–21 occurred within this interval.

2. Interplanetary and Geomagnetic Observation

According to Gonzalez et al. (2001) and Vieira et al. (2001), the dominant interplanetary phenomenon causing intense magnetic storms are the interplanetary manifestation of fast coronal mass ejections (CMEs). Two interplanetary structures are important for the development of such class of storms: the sheath region just behind the forward shock, and the CME ejecta itself. Frequently, these structures lead to the development of intense storms with two-step growth in their main phase. These structures also lead sometimes to the development of very intense storms, especially when an additional interplanetary shock is found in the sheath plasma of the primary structure accompanying another stream (Gonzalez et al. 2001).

The orientation of the interplanetary magnetic field (IMF) carried by the solar wind is also a very important factor. Geomagnetic activity is known to enhance dramatically whenever the IMF is directed southward. It is well established that the B_z component of the IMF is the most important influence on the magnetosphere and high-latitude ionosphere, as it controls the fraction of the energy in the solar wind which is extracted by the magnetosphere. When B_z is strongly negative, magnetic reconnection between the IMF and the geomagnetic field produces open field lines which allow mass, energy and momentum to be transferred from the solar wind to the Earth's magnetosphere (Davies et al. 1997). Gonzalez and Tsurutani (1987) have also suggested that the IMF structures leading to intense magnetic storms have an intense and long duration southward component.

It is important to note that in several occasions more than one interplanetary structure can be associated with the origin of intense storms. These structures include complex structures. Such complex structures have received attention in literature (Burlaga et al. 1987, 2001, Behannon et al. 1991, Gonzalez et al. 2001, 2002). According to Dal Lago et al. (2001), most of the reported complex structures involve a fast forward shock followed by a magnetic cloud, and usually another high-speed stream is found in the magnetic cloud.

Figure 1a is a composition of the interplanetary and geomagnetic observations for the periods March 12–15 and October 18–21, 1989. While Fig. 1b presents those March 31–April 3, 1973. The storms are summarized using the low-latitude magnetic index D_{st} (Buonsanto and Fuller-Rowell 1997, Kamide 2001, Gonzalez et al. 2001, 2002, Tsurutani et al. 2004, Vieira et al. 2001) and is interpreted using available interplanetary data. The plots in Figs 1a and 1b show from top to bottom: the low-latitude magnetic index D_{st}, the interplanetary magnetic field component B_z, the solar wind flow speed, the proton number density, the plasma beta, plasma temperature, and the dawn-dusk electric field. These hourly data are from the National Geophysical Data Centre's SPIDR OMNI IMF data (http://spidr.ngdc.noaa.gov) and NSSDC's OMNIWeb Service (http://nssdc.gsfc.nasa.gov/omniweb).

As seen in the plots it appears the coronal mass ejections which took place during the magnetic storms in March 1989 had so extreme parameters that spacecraft based instruments for measurement of plasma characteristics in the near-Earth space were unable to work under such conditions. The implication of this situation is that the morphology of the ionospheric F2 region response to this intense geomagnetic storm may not be fully understood.

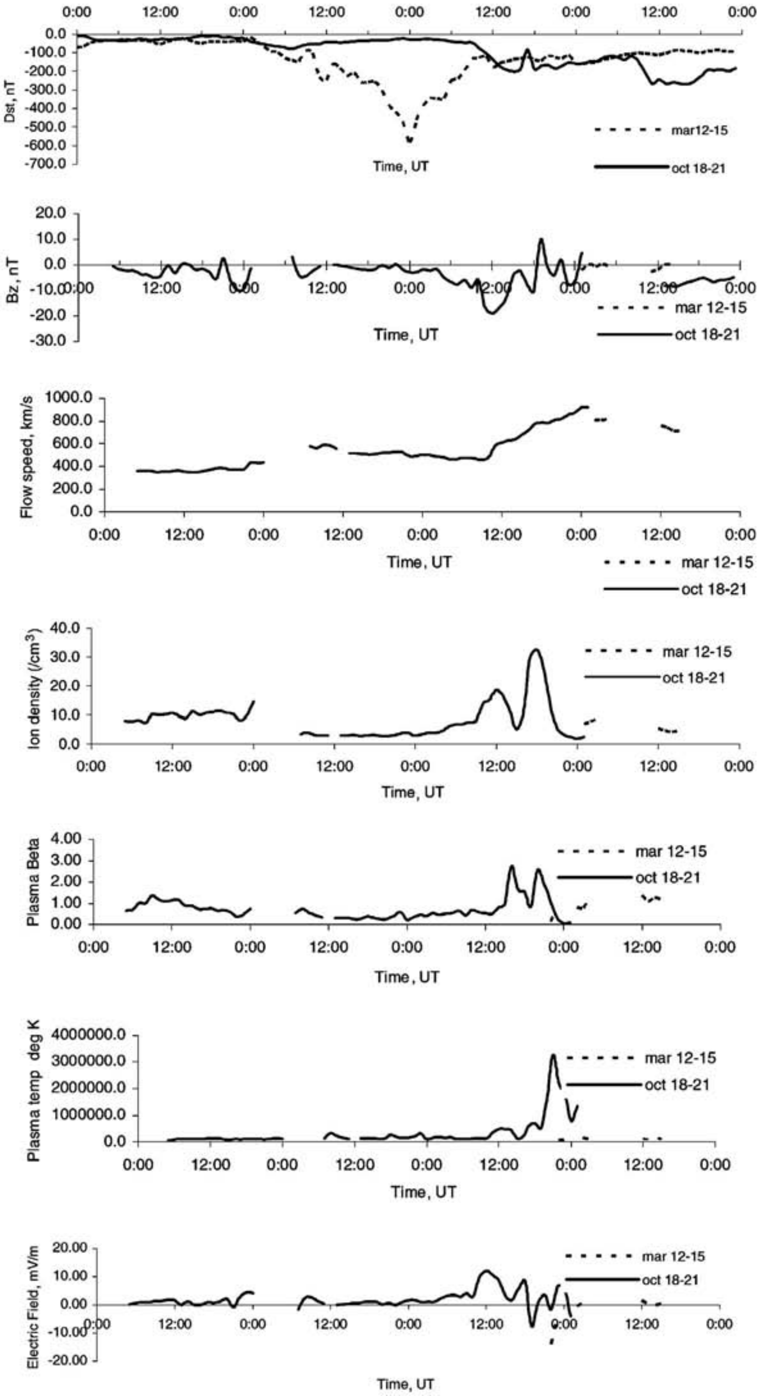

Fig. 1a. Composition of interplanetary and geomagnetic observations for March 12–15 and October 18–21, 1989

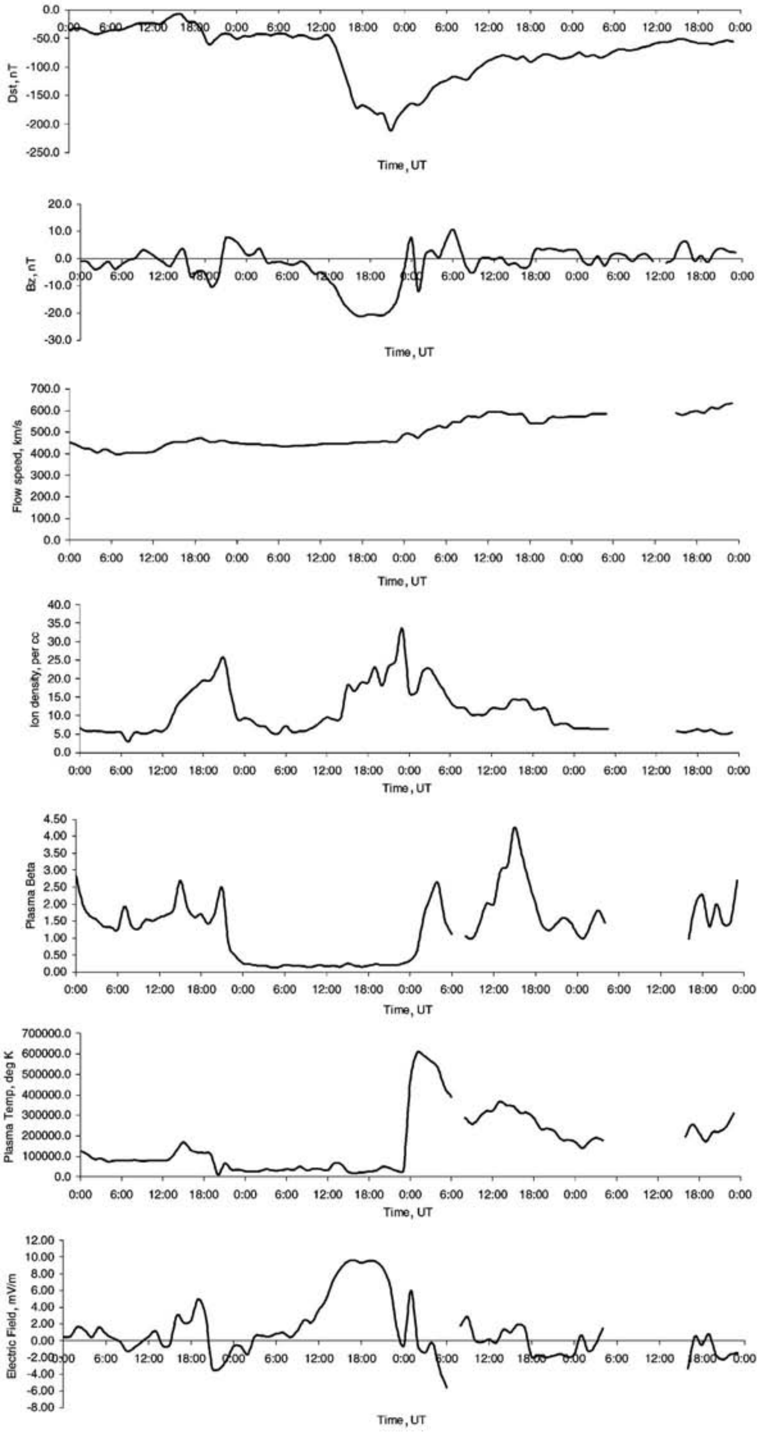

Fig. 1b. Composition of interplanetary and geomagnetic observations for March 31–April 3, 1973

March 13–14, 1989 storm

As shown in Fig. 1a, there are no solar wind data for the very intense storm of March 1989 from which we could understand the interplanetary B_z structures responsible for the storm. But the D_{st} variations appear to reveal a slow 24-hour build-up that began with gradual commencement at ∼0100 UT on March 13. Storms can be classified as follows: weak ($D_{st} > -50$ nT), ($-50nT < D_{st} < -100$) and intense ($D_{st} < -100$ nT) (Vieira et al. 2001). According to this classification, the D_{st} plot indicates that at 0600 UT on March 13 the D_{st} had decreased to a value of –128 nT indicating the commencement of an intense storm. D_{st} got to a minimum peak value of –143 nT at 0800 UT on March 13. D_{st} recovers rather gradually to –101 nT at 1000 UT and thereafter decreased to –246 nT at 1200 UT. D_{st} recovered again at 1300 UT to a value of –160 nT before decreasing sharply to minimum peak value of –583 nT at 0000 UT on March 14. The D_{st} variation between 0100 and 1300 UT deserves some comment in the absence of interplanetary B_z data. The recovery of D_{st} beginning at 0800 UT and 1200 UT respectively are indicative of turning B_z northward. Geomagnetic activity is known to decrease precipitously whenever IMF is directed northward (Chaman-Lal 2000). While 1000 UT and 1300 UT appear to mark southward turning of B_z. Geomagnetic activity is known to enhance dramatically whenever the IMF is directed southward. Such a configuration tends to increase the coupling between the solar wind and the magnetosphere with the result that relatively more solar wind energy can then enter the magnetosphere (Chaman-Lal 2000). According to Daglis (1997) and Kamide et al. (1998b), if a new major particle injection occurs it leads to a further development of the ring current with D_{st} index decreasing. Furthermore, if we accept the aforementioned orientations of B_z then it will be convenient, as a first approximation, to assume the presence of a magnetic cloud during this period. According to Tsurutani et al. (2003) magnetic clouds that are geoeffective have a southward and then northward (or vice versa) magnetic field directional variation. When the magnetic cloud has a very high velocity — that is if the speed differential between the CME and the slow, upstream solar wind is greater than the magnetosonic wave speed (50–70 km/s), it compresses the plasma ahead of it and forms a "collisionless" shock. Behind this shock is a sheath, which contains heated plasma and compressed magnetic fields. These intense sheath magnetic fields can also cause magnetic storms. It is important to note that whether intense interplanetary fields are those of sheath or the ejecta, the energy injection mechanism into the magnetosphere is the same (Gonzalez et al. 2002). If both the sheath field and the cloud field have the proper orientation, there will be magnetic reconnection from both phenomenon and a "double storm" (Kamide et al. 1998a) will result. In complex cases where there are multiple solar flarings there will be multiple solar ejecta, multiple shocks, and thus multiple plasma and field compressions. Triple storms, etc. will result (Tsurutani et al. 2003), and the main phase of the March 13–14 storm appears to show a triple-step storm. It pertinent to note that March 1989 was a period of some extraordinary activity. Starting from March 6th when there appeared a large sunspot region on the eastern edge of the sun and a remarkable solar flare of X-ray class of X15.0.The next 14 days produced 11 “X class” flares and 48 “M class”. These flares would result in a sequence of CMEs.

October 20–21, 1989 storm

The B_z plot for October 18–21 first indicates a change in B_z of $\delta B_z = 12.2$ nT between 2100 and 2300 UT on October 18 which appear to coincide with increases in both plasma density and flow speed. Associated with this change in B_s is the first decrease in D_{st} at ∼2000 UT. D_{st} which got to a minimum value of –80 nT at 0700 UT on October 19 from a value of –7 nT at ∼2000 UT on October 18. Vieira et al. (2001) had classified as moderate storms geomagnetic storms with D_{st} in the range: (-50 nT $< D_{st} < -100$). We would want to argue that the solar wind became geoeffective between 2100 and 2300 UT on October 18. According to Daglis (1997) and Kamide et al. (1998), if a new major particle injection occurs it leads to a further development of the ring current with D_{st} index decreasing. Note also that the increases in both plasma density and flow speed are indicative of arrival of a shock in the interplanetary medium. The solar wind speed increased from ∼372 to ∼431 kms^{-1} during this time interval. According to Kane (2005), moderate or strong storms occurred only when solar wind speed was above ∼350 kms^{-1}. And we would want to presently note that the aforementioned change in B_z could lead to the explanation of ionospheric responses observed at some stations hours after it occurred. This is because Davis et al. (1997) have shown that a southward turnings with a change in B_z of $\delta B_z > 11.5$ nT results in f_{o}F2 showing a marked decrease in amplitude, reaching a minimum value about 20 hours after the southward turning. The plot thereafter shows that the arrival of another shock in the interplanetary medium at ∼1000 UT, on October 20. This is indicated in part, as reported in Chukwuma (2003b), by near-coincident increases in plasma density and velocity. Note that between 1000 and 1300 UT on October 20 the B_z component of the IMF was strongly negative. A major storm occurs when the IMF experiences more than three hours and more than 10 nT southward component (Gonzalez and Tsurutani 1987). Associated with this large increase in B_s is the first decrease in D_{st} at ∼1000 UT. This event indicates that the solar wind plasma becomes highly geoeffective near 1000 UT (Chukwuma 2003b). Hence apart the moderate storm of October 19, the D_{st} plot presents a three-step main phase event that took over 24 hours to develop: In the first step of the main phase the D_{st} reaches the peak value of –202 nT at 1500 UT on October 20. With the sharp rotation of B_z to northward there is a sharp partial D_{st} recovery to the level of –101 nT. Geomagnetic activity is known to decrease precipitously whenever IMF is directed northward (Chaman-Lal 2000). The second step of the main phase is associated with the sharp southward turning of B_z at 1600 UT. Thereafter D_{st} and B_z reach peak values of 186 nT and –10.2 nT respectively at 1800 UT on October 20. Note the large increase in proton density beginning at 1500 UT. According to Daglis (1997) and Kamide et al. (1998b), if a new major particle injection occurs it leads to a further development of the ring current with D_{st} index decreasing a second time. After B_z has reached the peak value, it sharply rotates to northward. This decrease in the intensity of the southward component of the magnetic field is followed by a recovery in D_{st}. A significant data gap is present in the measured parameters of solar wind plasma and IMF components for 11 hours beginning at 0200 UT on October 21. Paucity of data would not allow comments on the IMF during this period. However, third step of the main phase began with the rapid decrease in the D_{st} at 0800 UT on October 21. In this phase D_{st} reaches the peak value of –268 nT at 1600 UT. This being the lowest value of D_{st} for this whole storm. The third phase confirmed the October 20–21 storm a intense geomagnetic storm and results from the enhancement of the second phase. According to Gonzalez et al. (2002) one way of getting large D_{st} events is to have two-step storm main phases, with the second enhancement of the D_{st} index closely following the first one (Tsurutani and Gonzalez 1997). Furthermore, Kamide et al. (1998a) argue that this could also be viewed as two "moderate" magnetic storms with the base of the second well below that of the first. Kamide et al. (1998a) have shown that such events are quite common and are caused by two IMF southward field of approximately equal strength. The storm recovery phase appears associated by a gradual turning of the IMF to a northward direction (Chukwuma 2003b).

The structure of the geomagnetic storm of October 20–21 storm is made clearer by the flow speed, Plasma density, Plasma Beta, Plasma temperature and the Electric field plots. The plasma beta plot shows a value range of 0.22–2.55 for October 20. For this same day, the plasma temperature was, after the arrival of the shock, mostly in the range: 480,000–1600,000 deg/k. It transpires from the high plasma beta, and plasma temperature values that the shock was followed by ejecta which was not a magnetic cloud type (Dal Lago et al. 2004). A magnetic cloud is a region of slowly varying and strong magnetic fields (10–25 nT or higher) with exceptionally low proton temperature and plasma beta typically $\approx$0.1. (Burlaga et al. 1981, 2001, Gonzalez et al. 2002 and references therein). Following this ejecta, one can observe a high speed stream, which is overtaking it. The interaction of the high speed stream and ejecta results in an increase in speed, density and temperature (Dal Lago et al. 2004). Probably this interaction would have resulted in the compression and intensification of the magnetic field of the ejecta which lead to the third step.

April 1–2, 1973 storm

We had earlier observed that Fig. 1b presents a composition of the interplanetary and geomagnetic observations for the period March 31–April 3, 1973. The D_{st} plot indicates that from 0000 to 1600 UT on March 31, 1973, the D_{st} values have been between –35 and –8 nT. However, beginning from 1600 UT on the same day, D_{st} was depressed gradually to –60 nT at 2000 UT a value that represents a moderate storm. Thereafter, D_{st} recovered gradually to about –43 nT at 2300 UT and remained at about this level until 1300 UT on April 1 when it was depressed rather sharply to –167 nT at 1800 UT, before getting to a minimum peak value at 2200 UT on the same day. Thereafter D_{st} recovers rather gradually throughout April 2, 1973. The D_{st} plot is indicative of a double step storm in which D_{st} reached its lowest value in the second step.

The B_z plot shows that until about 1500 UT on March 31 there was no definite trend in B_z variations. At ∼1500UT there came a sharp southward turning of B_z. At 1900 UT B_z reaches a peak value of –10.4 nT indicating that the IMF has experienced about four hours of southward component. Note also a change in B_z of $\delta B_z = 13.6$ nT between 1500 and 1900 UT. Davis et al. (1997) have shown that a southward turnings with a change in B_z of $\delta B_z > 11.5$ nT results in $f_{\rm o}$F2 showing a marked decrease in amplitude, reaching a minimum value about 20 hours after the southward turning. It is important to note that the southward turning of B_z at ∼1500 UT appear have to triggered the depression of D_{st} beginning from 1600 UT. At ∼2100 UT B_z had rotated northward and attained a value of 7.3 nT. From ∼2200 UT on March 31 B_z still pointing northward began to decrease then rotated southward reaching a minimum value of –2.2 nT at 0700 UT. Thereafter it sharply attains a peak value of –21.2 nT at 1700 UT on April 1. B_z remained southward until ∼0000 UT on April 2 when it sharply became northward. According to Gonzalez and Tsurutani (1987), the IMF structures leading to intense magnetic storms have intense (> 10 nT) and long duration (> 3 hr) southward component. According to Kane (2005), the duration for which B_z is negative is important factor in the relationship of solar and interplanetary plasma parameters with geomagnetic storms.

The flow speed plot shows a moderate-speed stream from 0000 UT to ∼1400 UT. The stream got to a peak value of 472 kms^{-1} at 1900 UT on March 31. Thereafter, the speed decreased getting to a minimum value of 434 kms^{-1} at 0700 UT on April 1. It s worthy of note that in the period March 31–April 1 the solar wind never attained the 500 km/s; in which case it could never met the criterion of fast solar winds. However, we want to point out that geomagnetic storms could occur at the solar wind speed shown in the plot. According to Kane (2005), moderate or strong storms occurred only when solar wind speed was above ∼350 kms^{-1}. Above this limit, any value of the solar wind speed, V, could be associated with any value of D_{st} in a wide range of a factor of ∼2, or any value D_{st} could be associated with any value of solar wind speed in a wide range of a factor of ∼2 (Kane 2005). Furthermore, it has been noted that when the magnetic field of the interplanetary feature engulfing the Earth has a strong southward component B_s, as it was between 1300 and 1700 UT with respective values of $-10.9 \text{ nT} < D_{st} < 21.2$ nT, a good relationship is obtained between D_{st} and the product VB_s (Wang et al. 2003). This partly because not V but VB_s is the appropriate variable relevant for D_{st} changes (Kane 2005). The plot further indicates the beginning of a high speed stream at 2200 UT. This high speed stream got to a peak speed of 593 kms^{-1} at 1200 UT on April 2 before decreasing to minimum value of 543 kms^{-1}.

The proton number density plot presents the proton number density increasing from ∼1400 UT on March 31. The proton number density got to a peak value of 25.5/ cm^3 at 2100 UT on March 31. The large increase in the proton number density during this period signals the arrival of a shock in the interplanetary medium (Strickland et al. 2001). Between 2300 UT on March 31 and 1400 UT on April 1 the proton number density was at its minimum values. However, beginning from 1400 UT on April 1 there was a rapid increase in the proton number density which got to a peak at value of 33.4/ cm^3 at 2300 UT. This rapid increase in the proton number density appears to indicate of the presence of a CME ejecta containing a magnetic cloud (Chukwuma 2005).

The plasma beta panel shows that the plasma beta has relatively high beta values throughout March 31, with sharp increases to the values of 2.69 and 2.47 at 1500 UT and 2100 UT respectively. And starting from about 0400 UT on April l, the plasma beta values became very low. As shown, the day was marked by low beta values ranging from 0.14 to 0.25. At ∼0000 UT on April 2, the beta values increased sharply reaching the value of 2.62 at 0400 UT.

The plasma temperature plot shows that the pre-noon plasma temperature on March 31 was marked mostly by low temperature. However, at ∼1500 UT there came along a rather abrupt rise in temperature to a peak value of 168687.0°K. The increase in the temperature at this hour is indicative of the arrival of a shock in the interplanetary medium. Thereafter, plasma temperature decreased gradually to a minimum value of 8842.0°K at 2000 UT. It however increased to 65761.0°K at 2100 UT before decreasing to 26712.0°K at 0000 UT on April 1. This relatively low temperature was mostly maintained throughout the day until ∼2300 UT when the temperature increased sharply to 605845.0°K. Thereafter the temperature started to decrease reaching the value of 256280.0 at 0900 UT on April 2. It's convenient to suggest at first approximation the existence of a magnetic cloud in the interval between 0100 and 2300 UT April 1. Our suggestion is due to low plasma beta values which are coincident with low proton temperature.

The interplanetary duskward electric field is given by $-V \times B_z$. The bottom panel of Fig. 1b presents the electric field plot. It shows that throughout March 31, the electric fields were less than 5.00 mV/m. The situation remained the same during most of pre-noon hours of April 1. At ∼1100 UT on April 1, the electric field began a gradual increase getting to a value of 9.43 mV/m at 1600 UT. Four hours later it now got to its peak value of 9.48 mV/m at 2000 UT. These electric field conditions which gave $B_z > 10$ nT are indicative of an intense storm.

3. Ionospheric data and method of analysis

The ionospheric data used in this study consists of hourly values of f_oF2 obtained from some of the National Geophysical Data Centre's SPIDR (Space Physics Interactive Data Resource) global network of ionosonde stations. These stations are located in (i) East Asian sector: Wakkanai, Akita, Kokubunji, Okinawa, Chung-Li and Manila, (ii) Euro-African sector: Uppsala, Kaliningrad, Slough, Lindau, Kiev, Sofia, Rome and Ouagadougou (iii) American sector: Ottawa, Boulder, and Point Arguello. Table I lists the stations. It is important to note that paucity of data at most stations during the days under investigation restricted our choice of ionosonde stations.

The present study is concerned with variations in f_oF2 due to the geomagnetic storms of March 13–14, 1989, October 20–21, 1989 and April 1–3, 1973. However, the F2 region response to geomagnetic storms is most conveniently described in terms of $D(f_\mathrm{o}\mathrm{F2})$, that is the normalized deviations of the critical frequency f_oF2

Table I. Ionosonde stations

Station	Geographic co-ordinates		Geomagnetic co-ordinates		Difference between LST and UT (in hours)
	φ	λ	φ	λ	
East Asian sector					
Wakkanai	45.40°N	141.70°E	35.62°N	207.30°E	+9
Akita	39.70°N	140.10°E	29.72°N	206.70°E	+9
Kokubunji	35.70°N	139.50°E	25.70°N	206.70°E	+9
Okinawa	26.30°N	127.30°E	15.45°N	196.40°E	+8
Chung-li	25.00°N	121.50°E	14.35°N	191.90°E	+8
Manila	14.70°N	121.00°E	3.57°N	191.10°E	+8
Euro-African sector					
Uppsala	59.86°N	17.64°E	58.30°N	107.20°E	+1
Kaliningrad	59.70°N	20.60°E	57.64°N	109.50°E	+1
Slough	54.50°N	359.40°E	56.89°N	86.20°E	0
Lindau	51.60°N	10.10°E	52.05°N	95.00°E	+1
Kiev	50.50°N	30.50°E	47.12°N	113.40°E	+2
Sofia	42.70°N	23.30°E	40.96°N	103.80°E	+1
Rome	41.80°N	11.83°E	42.20°N	92.80°E	+1
Ouagadougou	12.40°N	1.53°E	15.42°N	75.30°E	0
American sector					
Ottawa	45.40°N	284.10°E	56.68°N	353.00°E	–5
Boulder	40.00°N	254.70°E	48.93°N	318.20°E	–7
Point Arguello	35.60°N	239.40°E	42.32°N	302.40°E	–8

from the reference:

$$D(f_{\mathrm{o}}\mathrm{F2}) = \frac{f_{\mathrm{o}}\mathrm{F2} - (f_{\mathrm{o}}\mathrm{F2})_{\mathrm{ave}}}{(f_{\mathrm{o}}\mathrm{F2})_{\mathrm{ave}}} .$$

Hence, for the March 1989 storm, the data that was analysed consists of $D(f_{\mathrm{o}}\mathrm{F2})$ of respective hourly values of $f_{\mathrm{o}}\mathrm{F2}$ on March 13, 14, and 15. The reference for each hour is the average value of $f_{\mathrm{o}}\mathrm{F2}$ for that hour calculated from the three quiet days 10–12 March 1989, preceding the storm. Also, for the October 1989 storm, the data that was analysed consists of $D(f_{\mathrm{o}}\mathrm{F2})$ of respective hourly values of $f_{\mathrm{o}}\mathrm{F2}$ on October 20, 21 and 22. The reference for each hour is the average value of $f_{\mathrm{o}}\mathrm{F2}$ for that hour calculated from the three quiet days, October 17–19, 1989, preceding the storm. The hourly $D(f_{\mathrm{o}}\mathrm{F2})$ data for the April 1973 storm are from respective hourly values of $f_{\mathrm{o}}\mathrm{F2}$ obtained from April 1–3, 1973. The reference for each hour is the average value of $f_{\mathrm{o}}\mathrm{F2}$ for that hour calculated from the four quiet days March 27–31, 1973. The use $D(f_{\mathrm{o}}\mathrm{F2})$ rather than $f_{\mathrm{o}}\mathrm{F2}$ provides a first-order correction for temporal, seasonal and solar cycle variations so that geomagnetic storm effects are better identified. Furthermore, the criterion used in selecting the stations is such that storm variations represented real changes in electron density not simply redistribution of the existing plasma (Chukwuma 2003b).

4. Results and discussion

March 13–14 and October 20–21, 1989 storm

Plots illustrating $D(f_o\mathrm{F2})$ vs. UT for 13–15 March 1989 for the East Asian sector, for October 20–22, 1989 for the Euro-African sector, and for the American sector for both 13–15 March 1989 and October 20–22, 1989 are respectively provided in Fig. 2 a,b and c. As shown, there is no evidence of the phenomena under investigation in the plots for the East Asian sector. Furthermore, there is no immediate effect on f_oF2 following sudden commencement. However, by mid day of 13 March a depletion of f_oF2 became obvious at all the stations irrespective of their latitude. This is with the exception of the lower latitude station of Manila (14.7°N). On 14 March, a definite pattern begins to emerge from available data with respect to 0000 UT. As presented, all the stations indicated on the average some degree of simultaneity in the depletion of f_oF2. Furthermore, f_oF2 appears to be reduced by $\sim$60% from reference level before midday, and thereafter f_oF2 started recovering from 1200 UT and continued throughout 15 March 1989 (Chukwuma 2003a). In Euro-African sector there is no immediate effect on f_oF2 in the ionosphere above Rome (41.8°N) and Sofia (42.72°N) following storm commencement. But positive storm preceded storm commencement at Slough (54.4°N) and Uppsala (59.86°N). These are middle latitude stations. Blagoveshchensky et al. (2003) had also observed positive storms at mid-latitude stations of the European sector prior to the May 15, 1997 storm and suggested that the occurrence of the positive storm can be explained by an increase of the K_p index to 3^+ hours to the storm commencement. This explanation appears insufficient because Davis et al. (1997) have shown that K_p rises before the southward turning of B_z. Note the existence of negative storm, at the lower latitude station of Ouagadougou (12.4°N) hours before storm commencement. Presently, we would want to define positive and negative storms by changes in amplitude (the maximum absolute value of $D(f_o\mathrm{F2})$) of more than 10% (Danilov 2001).

For the American sector, Fig. 2c does not indicate the appearance of positive storm before the beginning of the geomagnetic disturbances of 13–15 March 1989 and October 20–22, 1989 at Boulder and Point Arguello. It is important to note that for this investigation we analyzed 19 f_oF2 data sets from ionosonde stations in the three sectors for the two geomagnetic storms. However, we have omitted the plots for the Euro-African sector for the 13–15 March 1989 geomagnetic storm as well as the plots for the East Asian sector for October 20–22, 1989 storm. These omissions are as a result of space constraints and are justified by the absence, in these plots, of the phenomena under investigation. As shown the phenomena under investigation were only observed in only three of the nineteen plots representing $\sim$16% occurrence.

The positive storm at Slough (54.4°N) and Uppsala (59.86°N) and the negative storm, at the lower latitude station of Ouagadougou (12.4°N), appear to be caused by the southward turning of B_z at $\sim$2100 UT which got to a change in B_z of $\delta B_z = 12.2$ nT at 2300 UT on October 18. Davis et al. (1997) have shown that a southward turnings with a change in B_z of $\delta B_z > 11.5$ nT results in f_oF2 showing

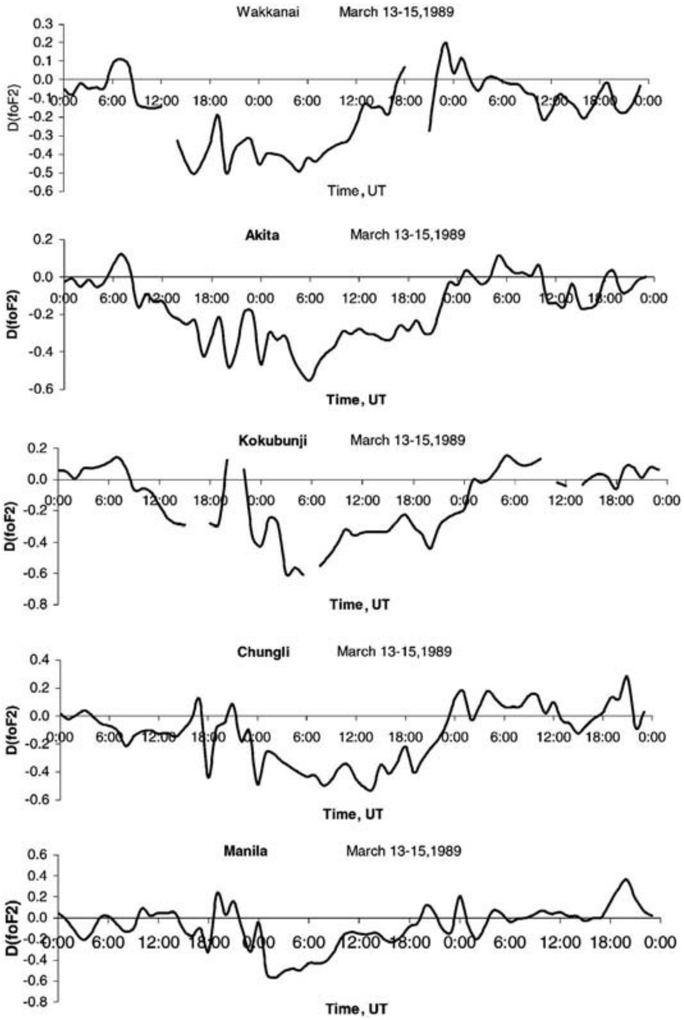

Fig. 2a. Variations in D(f_{o}F2) in East Asia for March 13–15, 1989

a marked decrease, reaching a minimum value about 20 hours after the southward turning and is assumed as an indication that energy is deposited at high latitudes which leads to ionospheric disturbances. It appears the southward turning with a change in B_z of $\delta B_z = 12.2$ nT may have been accompanied by an increase in solar wind dynamic pressure which led to an enhanced coupling between the solar wind and the terrestrial magnetosphere that significantly increased the geoeffictiveness of the solar wind (Boudouridis et al. 2005). According to Davis et al. (1997), although negative IMF is important in enabling the extraction of solar wind energy and thus driving global ionosphere/thermosphere disturbances, the solar wind energy density (proportional to dynamic pressure) must be high for coherent changes to be seen at mid-latitudes. Chukwuma (2003b) had explained the depletion of f_{o}F2 during

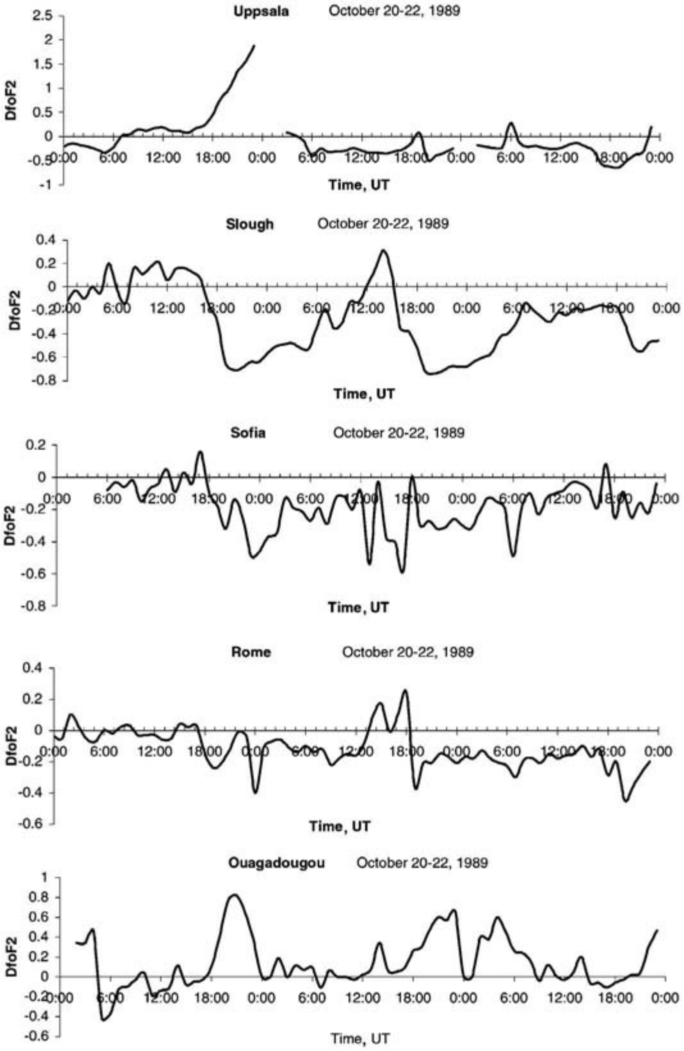

Fig. 2b. Variations in D(f_oF2) in Euro-African for October 20–22, 1989

the October 20–21, 1989 geomagnetic storm on the basis of a storm commencement at 1000 UT on October 20. But it is important to note that between 1000 and 1300 UT on October 20, the B_z component of the IMF also indicated a change in B_z of $\delta > 11.5$ nT and as shown in Table II, after the B_z southward turning on October 20, the maximum depletion of f_oF2 at the stations occurred on October 21 and 22 after respective interval comparable with the period between the southward turning of B_z at ∼2100 UT on October 18 and the observation of the phenomena under study on October 20. Given this result, we would want to argue from the results of Davis et al. (1997) that the solar wind became geoeffective at ∼2300 UT on October 18 when $\delta B_z = 12.2$ nT.

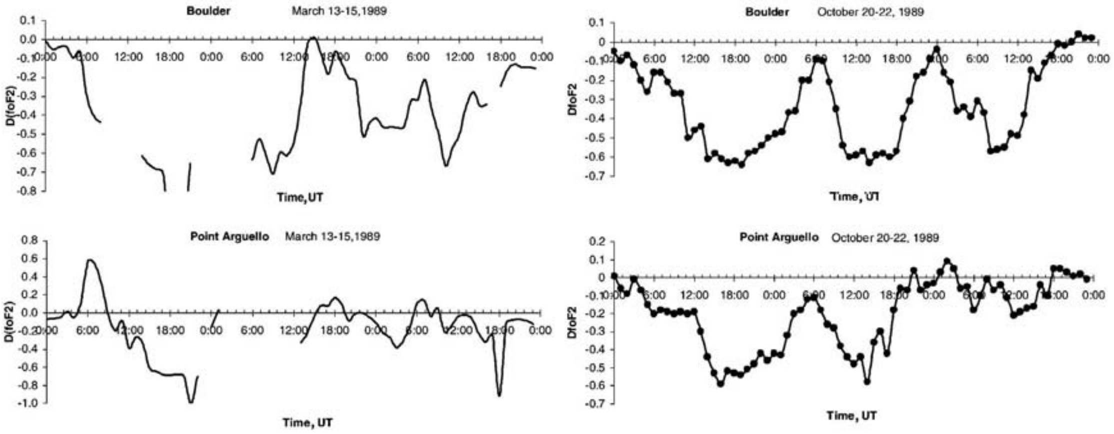

Fig. 2c. Variations in D(f_oF2) in American sector respectively for March 13–15, 1989 (on the left side) and October 20–22, 1989 (on the right side)

Table II. Maximum value of D(f_oF2) for negative storm in Euro-African for October 20–21, 1989 storm. Time of B_z turning is 1000 UT October 20, 1989

Station	Depletion %	Date October 1989	Time UT
Uppsala	48	21	2000
	64	22	2200
Slough	71	20	2000
	74	21	2000
Sofia	49	20	2300
	54	21	1300
	58	21	1700
	49	22	0600
Rome	24	20	1900
	40	21	0000
	36	21	1900
	45	22	2000

April 1–2, 1973 storm

Figure 3 a,b and c respectively provides the plots showing $D(f_o\text{F2})$ vs. UT for April 1–3, 1973 for the East Asian sector, the Euro-African sector and the American sector. Figure 3a shows that at Wakkanai, there was positive storm between 0500 and 1400 UT on April 1, 1973. The maximum enhancement during this period was ~30 % and it occurred respectively at 0500 and 1100 UT. This positive phase was followed by a negative storm which began at ~1800 UT on April 1 and got to peak depletion of 45% at 0100 UT on April 2, 1973. April 1, 1973 started at Akita with a positive storm having a electron density enhancement of ∼12% between 0000 and 0100 UT. This increase in electron density was again followed by a positive phase between 0500 and 1600 UT. The maximum enhancement during this phase was ∼35% at 0600 UT. Note the positive storm at 2000 UT. The electron density enhancement at this time is ∼25% and is followed immediately at ∼2100 UT by a negative storm which got to a peak depletion of 31% at 0100 UT on April 2, 1973. April 1 also started with a positive storm at Kokubunji. This positive phase lasted from 0000 to 1700 UT with a maximum electron density enhancement of ∼34% at 1000 UT. Note also the positive storm at 2000 UT. The electron density enhancement at this time is ∼35%. However, unlike at Akita the positive storm is not followed by a negative storm. $f_{\rm o}$F2 data was unavailable for most of the April 1, 1973 at Okinawa. However, between 0000 and 0500 UT when there was available data, there was no record of positive storm. On April 1, 1973, $f_{\rm o}$F2 data from Manila indicated a strong negative storm which appears to have started at ∼1800 UT with 34% depletion. This negative phase got to peak depletion of ∼100% at 2000 UT. The peak depletion at Manila preceded the intense geomagnetic storm by two hours. Furthermore, after the intense geomagnetic storm ($D_{st} = -211$ nT) at 2200 UT, the station recorded a positive ionospheric storm with electron density enhancement of 30%.

In Fig. 3b, there appear to be no positive ionospheric storm preceding the intense geomagnetic storm of April 1–2, 1973 at Kaliningrad, Slough and Lindau. However, the ionosphere at Kiev indicated a positive storm at 0600 with electron density enhancement of 12% from the reference level. Sofia as well recorded a positive storm in the period 0300–0400 UT with 21% electron density enhancement at 0300 UT.

$f_{\rm o}$F2 data from the stations in the American sector present evidence that positive ionospheric storm preceded the intense geomagnetic storm of April 1–2, 1973. Figure 3c shows that at Ottawa, there was a positive storm between 0500 and 0800 UT with peak electron density enhancement of 43% at 0800 UT. This storm was preceded by an initial positive storm which occurred between 0000 and 0100 UT. At Boulder, the positive phase also occurred between 0500 and 0800 UT with peak electron density enhancement of 45% at 0500 UT. Furthermore, Fig. 3c shows that Point Arguello recorded a large enhancement of electron density of 52% above the reference level at 0500 on April 1, 1973. This positive phase lasted until 0900 UT. Note the positive storms at 1500 and 1800 UT. The enhancements at these times were 14 and 15% respectively.

The plots in Fig. 3 clearly show the existence of positive storms at mid-latitude stations of the East Asian sector, the Euro-African sector and the American sector prior to the intense storm of April 1–2, 1973. It also indicated a strong negative storm at the low latitude station of Manila. As shown the phenomena under investigation were observed in nine of the thirteen plots representing ∼69% occurrence. The observed phenomena appear to be caused by the southward turning of B_z at ∼1500 UT which got to a change in B_z of $\delta B_z = 13.6$ nT at 1900 UT on March 31. Davis et al. (1997) have shown that a southward turnings with a change in B_z of $\delta B_z > 11.5$ nT results in $f_{\rm o}$F2 showing a marked decrease in value. As we argued

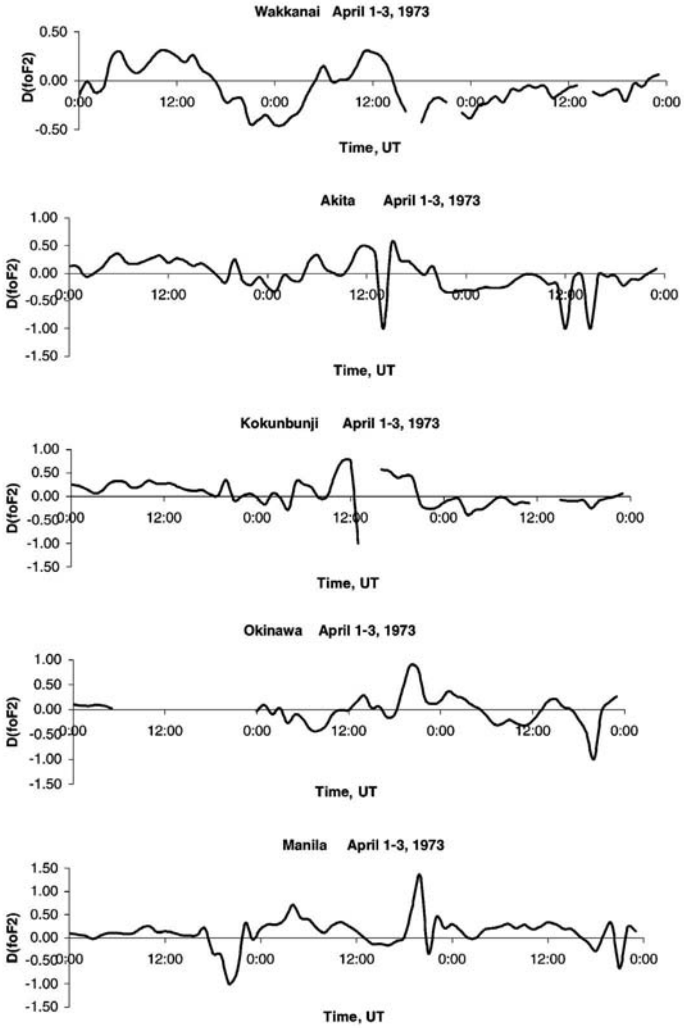

Fig. 3a. Variations in D(f_oF2) in East Asia for April 1–3, 1973

in the case of October 20–21, 1989 storm, it appears the southward turning with a change in B_z of $\delta B_z = 13.6$ nT may have been accompanied by an increase in solar wind dynamic pressure which led to an enhanced coupling between the solar wind and the terrestrial magnetosphere that significantly increased the geoeffictiveness of the solar wind (Boudouridis et al. 2005). It pertinent we observe that in the earlier study of the April 1–2, 1973 storm (e.g. Chandra and Spencer 1976), the investigation of the storm commenced at 0000 UT on April 1 and was limited only to April 1–3, and as such earlier interplanetary features which immediately preceded the intense storm and could be responsible for the phenomena under investigation were ignored. Even recently, in their investigation of the effects of the major geo-

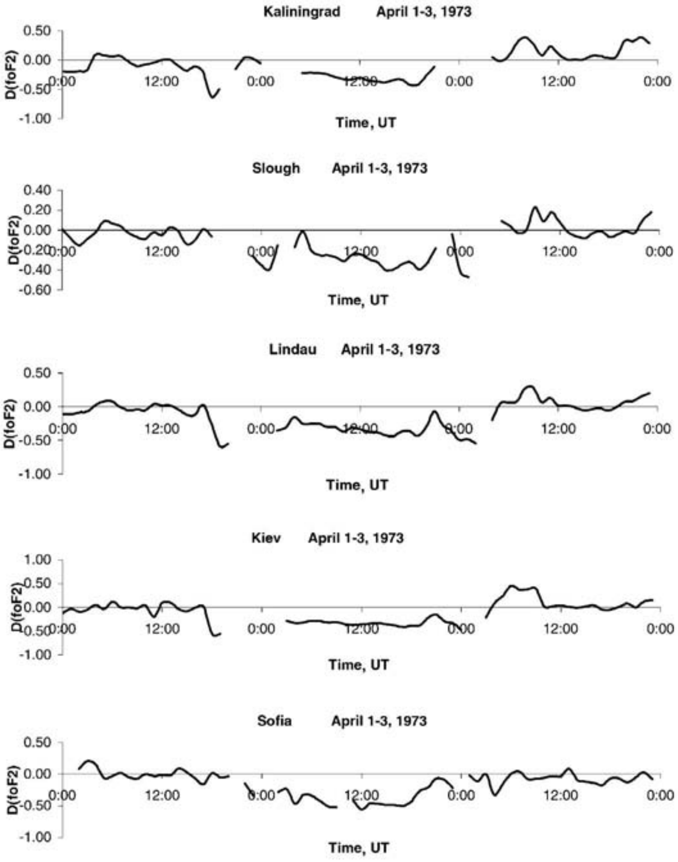

Fig. 3b. Variations in D(f_oF2) in Euro-African for April 1–3, 1973

magnetic storm of October 2003, on the equatorial and low-latitude F region, Sahai et al. (2005) only considered the D_{st} variations starting from 0000 UT on October 29 and limited the study to the intense storm days of October 29, 30 and 31, 2003.

5. Conclusion

The appearance of the positive storms at the mid-latitude stations and the negative storm, at the lower latitude stations can be explained as follows: As the solar wind became geoeffective, energy is injected into the polar upper atmosphere. This sudden energy addition launches a traveling atmospheric disturbance (TAD) which propagates with high velocity toward the equator, either directly or via the pole. An essential feature of such TAD is that it carries along equatorward-directed winds of moderate magnitude (150 m/s). According to Prolss and Ocko (2000), at middle latitudes these meridional winds drive ionization up inclined magnetic field lines and cause uplifting of the F layer. Since ionization loss (which are proportional to the N_2 and O_2 densities) decrease much faster with height than ionization pro-

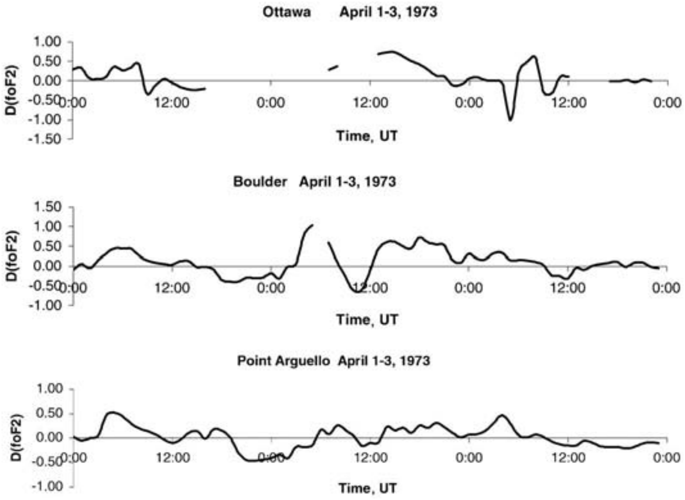

Fig. 3c. Variations in D(f_oF2) in American sector for April 1–3, 1973

duction (which is proportional to O density), this will lead to an increase in the ionization density i.e. positive storm. At low latitudes, the encounter of the two TADs launched in the northern and southern polar regions causes a compression and heating of the thermospheric gases (Fujiwara et al. 1996). Accordingly, the densities of all gas constituents will increase, with the largest enhancements seen in the heavier components N_2 and Ar (Prolss and Ocko 2000). This situation will lead to a decrease in the O/N_2 ratio. Given that electron concentration is directly proportional to the O/N_2 ratio at F2 layer maximum heights, there is a depletion of electron (negative storm). Note the absence of a wave-like phenomenon, in f_oF2 data at these stations, which is characteristic of TAD. It convenient to suggest that the TAD is a pulse-like atmospheric perturbation which is formed by a superposition of gravity waves (e.g. Testud et al. 1975, Richmond and Matsushita 1975 and Chang and St Maurice 1991). Thus, we are not dealing here with a wave-like oscillatory phenomenon.

According to Danilov (2001), the appearance of positive storms before the beginning of a geomagnetic storm in mid-latitudes and occurrence of negative storms at equator are some of the unresolved problems in ionospheric research. Presently we sought the prevalence of these phenomena and the results respectively show ∼16% and ∼69% occurrence for the case of March and October 1989, and in the case of April 1973 intense storm. We would want to argue that the non explanation of these phenomena is because in the studies of ionospheric storms it is assumed that the beginning of the disturbance is defined by an assumed onset of the magnetic storm. Now the onset of a magnetic storm is an all but well defined concept: The use of sudden storm commencement (SSC) as a reference time constitute a poor choice (Prolss 1995) because these impulse-like disturbance of the magnetic field are not associated with any significant energy deposition and are also observed after the onset of a magnetic storm, as indicated, for example, by the decrease in the D_{st} index (Akasofu 1970). Also the use of the main phase onset (MPO) for fixing the beginning of magnetic and ionospheric storms is fraught with problems that render a determination of the exact onset time difficult (Prolss 1995). This is because the main phase may proceed gradually, or in steps, or may follow a series of small perturbation. The notion of onset of the magnetic storm as a prevailing idea often restricted the geoeffectiveness of the solar wind to post onset time thereby foreclosing the explanation of any aspect of the morphology of ionospheric storms whose origin precede the onset reference time.

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